HIGH PRODUCTIVITY ALUMINUM MANUFACTURING

Final Phase 1 Report
for Period March 2012 – July 2013

Philip Gacka, William H. Grassel, Israel Stol, Kyle L. Williams, Daniel M. Myers, Kirit Shah, D. J. Spinella
Alcoa Inc.
Alcoa Technical Center
100 Technical Drive
Alcoa Center, PA 15069

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14. ABSTRACT

This report documents the first year of a two year program to develop single side, single pass butt welding capability of aluminum 5083 marine plate used for LCS construction. Welding process parameters and equipment techniques were developed to successfully weld 5/16" (8mm) thick plate. Technical limitations of this process made it unlikely it would be implemented in LCS shipyards. It was recommended not to continue this program to the planned second year, Phase 2 tasks.

15. SUBJECT TERMS

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1.0 Executive Summary

The ManTech High Productivity Aluminum Manufacturing program activity started in March 2012 per SCRA Base Task Order Agreement 2012-440. Under the direction of CNST, Alcoa Defense, Inc. (ADI) and its shipyard partners, Austal and Marinette, began a two year effort to develop and demonstrate a High-Deposition Gas Metal Arc (HDGMA) aluminum welding system. The goal was to enable single-sided, single-pass (SSSP) butt welding of select aluminum plate structures for both LCS classes of ships, Independence and Freedom. This two year program was broken into two phases with each phase being about 12 months in duration.

ADI's HDGMA aluminum welding system has the following innovations & benefits:

- Reduces multiple weld passes to a single pass (saves labor) and increases productivity;
- Eliminates the need for back-gouging (saves labor);
- Increases mechanization of welding operations, resulting in more consistent welds and fewer repairs (less rework);
- Reduces total welding heat input per linear length, thereby decreasing weld-induced distortion and rework (less rework time & materials);
- Reduces consumption of welding filler wire (material savings);

ADI's HDGMA aluminum welding process has the following implications, limitations and additional requirements compared to the Gas Metal Arc Welding (GMAW) process currently being used by shipyards.

- The maximum combined gap & vertical mismatch that will reliably produce a sound weld is 1.5mm gap, & 1.0mm vertical mismatch (increases labor for fit-up and/or eliminates some welds as candidates for HDGMAW);
- The process requires a bevel as part of the weld preparation for welding all thicknesses, to enable tactile seam tracking and to maintain the proper weld top (i.e. on face side) reinforcement height. Current shipyard practice typically does not require bevels on thinner material (increases labor);
- The process requires the use of a temporary backing bar to be placed-on the root side of joints to be welded to contain the root reinforcement and to allow for gas venting. This is an additional requirement, as compared to the Baseline GMAW processes used by the shipyards who were partners in this project.
- The edges of the root reinforcement must be ground to meet the re-entrant angle requirement for visual inspection (increases labor);

The cost saving target for HDGMAW was in the range of 30 to 35% savings for every dollar currently spent on aluminum plate butt welding in the flat down-hand position. A cost model was completed in Phase 1 to update the savings potential based on the factors listed above.

Phase 1, completed in July 2013, resulted in the development of procedures for flat down-hand welding of 5/16" thick (8mm nominal) 5083-H116 marine plate. Evaluation of horizontal out-of-position (OOP) HDGMAW welding was also done in Phase 1.

Toward the end of Phase 1, the state of HDGMAW technology development was reevaluated with respect to its expected readiness for implementation at the end of Phase 2. CNST determined that projected cost saving no longer justified continued process development. Three specific factors contributing to this assessment were:

1. Restrictive fit-up requirements between parts to be welded
2. The need for temporary back-up bars to be inserted beneath the weld seam
3. Backside weld grinding required to guarantee desired root weld reentry angle

ONR's Program Officer for CNST agreed with this assessment. This program was terminated after a modified Phase 1 task list was completed.

2.0 Program Goals and Objectives

Present practices for aluminum butt welding on LCS consist of labor-intensive and relatively costly procedures. Multiple weld passes are used to complete an aluminum weld. Besides requiring a high level of labor, multiple welding passes can result in extra weld induced distortion of weldments that requires rework. Aluminum panels and modules currently require welding from both sides. For panel line welding, this necessitates a multi-step procedure that includes:

- Preparing plate edges to be welded;
- Clamping and fixturing panels;
- Welding the joint through part of the thickness from one side with several weld passes;
- Flipping the panel assembly and re-clamping;
- Back gouging welds to prepare the weld areas on the side to be welded; and
- Welding the remainder of the joint from side two with several weld passes.

The differences between conventional and high deposition GMAW process are illustrated in Figures 1a and b.

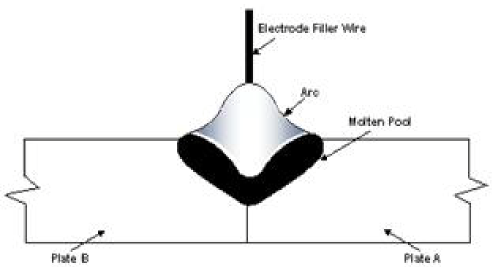

Figure 1A – Conventional GMAW

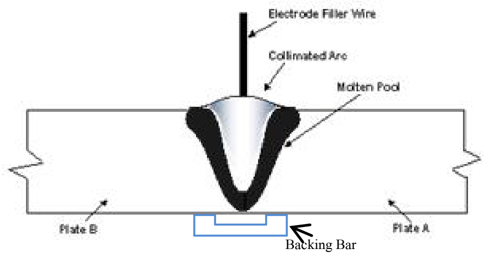

Figure 1B – High Deposition GMAW

This project's objective was to improve the current time-consuming and labor-intensive welding procedure by developing a mechanized welding method capable of single-sided, single-pass (SSSP) aluminum butt welding. Preliminary estimates of the cost savings potential of SSSP welding were in the range of 30 to 35% for every dollar currently spent on conventional aluminum flat down-hand butt welding. The Phase 1 cost model showed the potential savings for flat down-had (FDH) butt welding to be 21% for a total of $5300 in the case studied which had a total of 560 feet (170m) FDH welding. This savings estimate is affected by the assumption of the additional labor to meet the maximum gap and vertical mismatch limits for the HDGMAW process. ADI has made an estimate of this additional labor as being 1.5X that of the Baseline GMAW. This assumption should be refined by shipyard operating data. ADI did a sensitivity analysis to determine the breakeven point as a function of this additional labor. For the thickness considered in the cost model, the HDGMAW process would be the same overall cost if the multiplier was 2.6X. Also, due to the gap and vertical mismatch limitations, some welds may not be feasible with HDGMAW because the gap and vertical mismatch cannot be met regardless of the labor applied. It is not possible for ADI to estimate this, but, it has been cited as a concern by both Austal & Marinette Shipyards.

3.0 Program Team

SCRA Applied R&D is the Contractor for ManTech Task Order 2012-440. Under SCRA's management, the entities contributing to this program and specific areas of accountability are listed below.

Alcoa Defense, Inc. (ADI) provides technical leadership in the development of the equipment, processes, and procedures required for single side, single pass welding of aluminum marine plate. This includes experimental work to define specific welding parameters, selection of welding equipment, and preliminary cost saving assessments with respect to conventional GMAW practices. ADI works with LCS shipyard team members to obtain data needed to document current GMAW construction methods and data to compare with the new HDGMAW process.

Austal USA and Marinette Marine Corporation shipyard personnel monitor and contribute to the development of the HDGMAW system to ensure that its features are compatible with shipyard use. As requested by ADI, general shipyard welding practices, data, and weld samples are provided for comparison with HDGMAW.

American Bureau of Shipping (ABS) supports ADI by establishing and assessing weld quality targets the HDGMAW process must meet.

PMS 501 and NAVSEA 05 Navy personnel monitor all program developments, ensuring HDGMAW welds meet the Navy's technical requirements and economic expectations.

Personnel associated with the Phase 1 portion of this program are listed in Appendix 1.

4.0 Target Setting for Technical Development of Single Side, Single Pass Welding

4.1 Selection of Materials and Welding Parameters for Program Process Development

The official HPAM program kick-off meeting was held at the Alcoa Technical Center on March 27, 2012. One of the first program activities was to establish specific parameters Alcoa would use for initial HDGMAW process development.

During separate meetings with shipyard personnel in April, parameters for eleven different aspects of the HDGMAW system were determined. These system features described in Appendix 2 defined the initial parameters used for HDGMAW system development.

4.2 Configuration of HDGMAW System at ATC: Equipment Gap Analysis

Alcoa has done HDGMAW welding of various aluminum alloys and metal thicknesses over the past 10 years. This knowledge was applied to the current marine plate butt welding program to determine what equipment and ancillary materials would be required for process development.

Appendix 3 summarizes the resulting Gap Analysis. Alcoa equipment available for this program was identified in addition to equipment and materials that needed to be purchased or fabricated.

4.3 Welding Process Quality Specification

Appendix 4 contains metrics to assess welds produced by the high deposition GMAW process. These metrics were developed to provide a quantitative standard that HDGMAW joints would need to meet for use in production. These quality metrics were shared with the entire HPAM team in a meeting on May 31, 2012 and distributed by email on June 11, 2012. The email requested input from all team members. The Phase 1 Go-NoGo Checklist was distributed on September 27, 2012 and October 8, 2012. This checklist has a detailed listing of quality requirements from the specification. It was reviewed and presented as complete in the 2012 3rd Quarter Project Review Meeting and Minutes. The only reply received from the team on this topic was from NAVSEA on July 2, 2012. This reply specified that NAVSEA considered this a new welding process and required additional testing beyond those required for weld qualification. This email is included in Appendix 4. Reports for these tests are in Section 5.10 (Testing of HDGMAW for Acceptance as a New Weld Process).

5.0 HDGMAW Welding Parameters Development

5.1 Shielding Gas Selection and Qualification

Alcoa used an inert gas mixture of helium and argon as the shielding gas in past HDGMAW development. This prior work showed the benefits of the hotter, collimated arc obtained when using helium as a component of the shielding gas. Because of these past Alcoa welding experiences, the HPAM program started with a shielding gas composition of 75% He/25% Ar, with the full agreement of all the members of this program.

During the second quarter program review, representatives from Austal and Marinette expressed concern with including helium in the shielding gas composition. Helium was currently used for some welding at Austal, but helium was supplied on an allocation basis due to its limited availability. Marinette did not use any helium containing welding gas; all welding was done with 100% argon.

Alcoa agreed to determine if the HDGMAW process was viable with 100% argon shielding gas. Planned process development work was put on hold and all resources were allocated and directed toward assessing the potential of using only argon as the shielding gas with this welding technique.

Appendix 5 contains test data obtained using the HDGMAW process with shielding gas compositions of:

- 75% Helium / 25% Argon
- 25% Helium / 75% Argon
- 100% Argon

These data were reviewed during an entire program team meeting on August 07, 2012. There were obvious differences in weld cross-section using the three different shielding gas mixtures. However, each shielding gas produced welds with acceptable quality or with attributes that could be controlled by adjusting other process parameters. The team decided to continue process development with 100% argon shielding gas. Notes from this meeting are also included in Appendix 5.

5.2 Temporary Backing Bar Geometry and Plate Edge Preparation Determination

Because HDGMAW is used by welding from one side of joints, a temporary backing bar is used to support and contain the molten pool at the back side (i.e. root) of butt joints, until it solidifies. A recess in the backing bar is aligned with the weld seam. This recess helps to shape the solidifying metal. After a weld is completed, temporary backing bars are removed and cleaned for reuse or discarded.

Backing bars can be made from a variety of materials. The main technical requirement for a temporary backing bar is the capability to support and contain the molten pool of aluminum without fusing to the weld and becoming a part of it. Other considerations for the backing bar include the capability of effectively venting the pressure that builds up in its recess, the cost, the capability to be placed along the weld seam, and ease of removal after the weld is made.

A comparison of backing bar recess geometry was made to determine what to use for HDGMAW development. Appendix 6 compares the performance of ceramic backing bars with radii in the recess and anodized aluminum backing bars with rectangular recesses.

In these trials, neither backing bar geometry was capable of consistently shaping the root side of the weld, so it always meets the targeted root reentrant angle of greater than 90°. Any gap between the backing bar and the root side of the abutting parts resulted in a re-entrant angle of less than 90° on that side of the root reinforcement. For the backing bars with radii in their recesses and recesses that were either too shallow and/or too narrow, pressure build-up within these recesses was thought to contribute to the variability in weld geometry. To achieve the specified reentrant angle of greater than 90^0 at the back side of the welds, Alcoa recommended to grind the roots of the welds, regardless to whether they were produced with a radiused or non-radiused recesses in the backing bar. Backside weld grinding would be expected to be a manual operation along the entire length of the weld. This step was added to the cost model for the HDGMAW process. See the detailed cost model report in Section 5.11 for the cost contribution for this operation.

Recess depth in the Temporary Backing Bar as well as the bevel machined at the top edges of the butt joints were also found to affect the geometry of the weld root and height of the weld reinforcement, at the top (or face) side of the welds. Appendix 7 presents additional data from the welding evaluations used for selection of the top bevels and recess geometry for welding with the HDGMAW technique.

5.3 Establishing Parameters for the Baseline Welding Condition

Initial HDGMAW welding trials conducted with 5/16" (8mm) thick 5083-H116 plates, from April through September 2012, were used to determine welding process parameters to be used for systematic process development. Data from Appendices 6, 7, and 8 were the basis of a project review with all team members on October 04, 2012. Option 1 in Appendix 8 was selected for development of Baseline HDGMAW process parameters. The baseline was defined as butt welds with zero gap and zero vertical mismatch between plates. The baseline welding parameters are shown in Appendix 9. The welding system used for these trials is described in Table 1.

Table 1 – Lincoln GMA System

1. Lincoln Power Wave 455M Power Supply (program 40 Power Mode)
2. Lincoln Power Feed 25M Wire Feeder
3. MK Products Python Push Pull Welding Gun

5.4 Achieving Joint Gap and Vertical Mismatch Plate Position Goals

After developing the Baseline HDGMAW process parameters for butt welds with no joint gap or vertical mismatch between plates, the next program step was to determine whether the targeted combination of 0.060" (1.5mm) gap and 0.060" (1.5mm) vertical mismatch could be achieved per point 7 in Appendix 2.

Figure 2 shows that the baseline welding parameters (Appendix 9) were inadequate for accommodating the targeted variation in joint fit-up. As can be seen from Figure 2, joints with zero gap could be welded-with acceptable welds with an vertical mismatch of up to 0.1" (2.5mm). However, the largest plate gap that could be accommodated was 0.020" (0.5mm) at zero vertical mismatch. This limited gap accommodating capability was insufficient to meet the weld quality needs in the shipyard welding environment. As a result, Alcoa halted further process development with the initial baseline parameters and explored options to increase the joint gap accommodating-capability with the HDGMA welding technique.

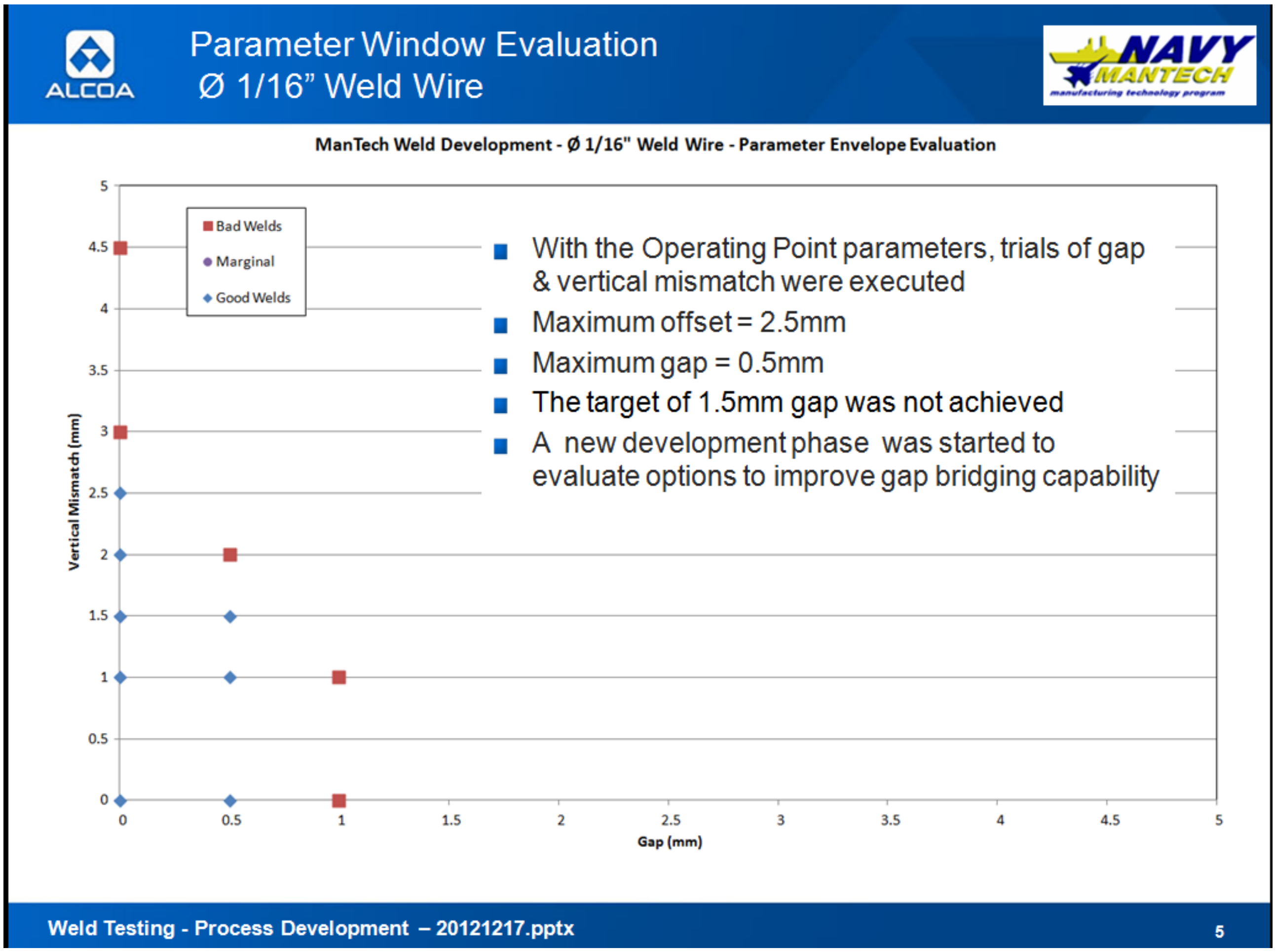

Figure 2 – Performance of Baseline HDGMAW With Plate Gaps and Vertical Mismatch

Ideas generated by Alcoa to increase the gap welding distance are shown in Appendix 10. The ideas are force ranked according to likelihood of success, where the first technique is the most "promising" and most likely to provide the sought after welding capabilities (i.e. increased forgiveness to variations in joint gaps and/or parts vertical mismatch) and the eighth one is the least likely to do so. These techniques were screened by rating them according to a visual examination of weld quality. Results are shown in Table 2.

Table 2 – Final Ranking of Methods to Increase HDGMAW Joint Gap & Vertical Mismatch Welding Capability

Final Rank	Option	Result	Implication
1	Larger Diameter Electrode - Weld wire was increased from 1/16" (1.59mm) to 3/32" (2.38mm)	Good Weld	Change power supply, weld wire less common, more heat input
2	Develop parameters to accommodate 2mm gap with current joint design - proove feasibility of Adaptive Fill Control	Good Weld	Requires laser seam tracker & complicated control system implemenation
3	Offset Torch Lateral Position - constant	Good Weld	Implementation complexity, unsure of effectiveness with veritcal mismatch
4	Change weld prep, Reduce Amps & Travel Speed (possible nominal gap)	Good Weld	Requires laser seam tracker & complicated control system implemenation
5	Square Butt, 1mm TBB Groove, 100% Argon	Marginal Weld	
6	Change weld prep - Single Bevel	Marginal Weld	
7	Reduce TBB Groove Depth - Single Vee 2mm Depth of Prep.	Bad Weld	
8	Back Hand Torch Angle - constant	Bad Weld	

Increasing welding wire diameter from 1/16" (1.59mm) to 3/32" (2.38mm) was found to be the most effective approach for better accommodating larger joint gaps and higher vertical mismatch between the parts. To weld with this larger diameter [i.e. 3/32" (2.38mm)] welding filler wire, the welding system was switched from the Lincoln system (Table 1) to the ESAB Welding system described in Table 3. The switch was necessary because the wire feeder of the Lincoln system was not capable of using 3/32" (2.38mm) weld wire. The ESAB welding system (Table 3) was used for Flat Down Hand welding development from this point on in the program.

Table 3 – ESAB GMA System

1. ESAB 652 CVCC Power Supply (CC Mode)
2. ESAB MIG 35 Wire Feeder
3. L-TEC ST-21 Push Welding Gun

To experimentally verify that welding with the larger 3/32" (2.38mm) diameter welding wire made the HDGMAW process more forgiving to joint gaps and vertical mismatch between parts, the 1/16" (1.59mm) diameter wire was also run with the ESAB 652 welding system. The results of welding with the 1/16 (1.59mm) diameter wire reconfirmed that welding with the 3/32" (2.38mm) diameter wire made the HDGMA welding process more forgiving to joint gaps and vertical mismatch between parts up to 0.080" (2mm).

The aforementioned results were shared with the entire project team on December 18, 2012. During this program review, five major open issues with welding with the 3/32" (2.38mm) diameter welding wire using the ESAB welding system were identified. These issues included:

- The transverse (to the weld) Ultimate Tensile & Yield Strengths and % Elongation (i.e. TYE) of the weldments produced with the 3/32" (2.38mm) diameter wire may be lower than the strengths of weldments produced with the original 1/16" (1.59mm) diameter wire, using the Lincoln welding system.
- The feasibility & ease of welding out of position with the HDGMAW technique may be affected. This concern stemmed from the fact that welding with the larger diameter 3/32"

(2.38mm) welding wire, would involve a larger molten pool, whose shape and movement may be adversely affected by gravity.
- The use of a 3/32” (2.38mm) diameter welding wire, which is commercially available, but less commonly used.
- Power Supply
    - The ESAB 652 CV/CC Power Supply is an older system and is not commercially available.
    - It will be necessary to program the waveform & speed of response on a current model to match the behavior of the ESAB 652 CV/CC.
- Wire Feeders
    - This availability of wire feeders 3/32” (2.38mm) wire that are compatible with the selected power supply will need to be investigated.

Austal and Marinette shipyard team members agreed that 3/32” (2.38mm) wire would be acceptable to use in production. The decision was made to resume Phase 1 of the HDGMAW development program using the 3/32” (2.38mm) diameter wire and the ESAB welding system.

5.5 Determination of Centriod, Final Parameters and Maximum Gap & Vertical Mismatch

Once the decision was made to use the 3/32” (2.38mm) diameter wire and the ESAB welding system, welding trials to determine welding parameters capable of accommodating larger joint gaps and vertical mismatch between parts and performance of the welds, were renewed. These welding trials started with the use of a temporary Backing Bar recess depth of 0.070” (1.78mm).

These welding trials revealed an improved tolerance to joint gaps up to 0.080” (2.0mm). However, the welding Parameter Operating Window was shown to be narrow, with the current operating range of 355±5 amps. Refer to Appendix 11 Figure A11-3 for the Parametric Envelope plot. Due to the depth of the 0.070” (1.78mm) recess in the backing bar, at the wider joint gaps the top weld reinforcement tended to sag and become concave and more difficult to control.

Based on these results, the recess depth was reduced to 0.050” (1.27mm) and Parameter Operating Window was again investigated. The shallower recess depth limited the tendency of the welds’ top reinforcement to sag and become concave, when welding larger joint gaps. With this recess depth in the Backing Bar, there was a significant improvement in the tolerance to 0.080” (2mm) gaps. This also widened the range of welding current/welding speed of travel combinations that could be used for producing sound and dimensionally acceptable welds with up to 0.080” (2mm) joint gaps. In addition, this shallower recess depth afforded the welding of up to 2mm vertical mismatch between parts, at 0mm joint gaps. Refer to the Parametric Envelope plot presented in Appendix 11 Figure A11-11.

Using the backing bar with the 0.050” (1.27mm) deep recess, HDGMA welding trials were carried out with different joint gap/vertical mismatch of parts combinations. The results from these trials showed that:
- Welding parts with 0.080” (2mm) Gap & 0.080” (2mm) Vertical Mismatch was not feasible.
- Welding parts with 0.080” (2mm) Gap & 0.060” (1.5mm) Vertical Mismatch was not

feasible.

- Welding parts with 0.060” (1.5mm) Gap & 0.060” (1.5mm) Vertical Mismatch resulted in inconsistent weld quality. Out of 16 welding trials, 6 welds were of unacceptable quality, 5 of marginal quality and 5 were of acceptable quality.
- Welding parts with 0.060” (1.5mm) Gap & 0.040” (1.0mm) Vertical Mismatch yielded welds with consistently acceptable weld quality and geometry. This joint gap & vertical mismatch combination became the maximums for welding these joints with the HDGMAW process.

The aforementioned details were presented at the team meeting on February 22, 2013, during which the concept was demonstrated by welding two 5 feet long pairs of plates. Appendix 11 presents the full report given at that meeting describing developmental activities and testing used to determine the acceptable parametric operating envelope. The welding system, equipment and welding conditions chosen to demonstrate the HDGMAW technique are shown in Tables 4 and 5, respectively.

Table 4 – Welding system and equipment used for welding with the 3/32” (2.38mm) diameter wire

- Power Source: ESAB 652 CV/CC
- Wire Feeder: MIG 35
- Torch/Gun: ST-21 – Push
- Backing: Type – Temporary – Rectangular Recess – 1.3mm (0.05”) x 25.4mm (1.0”), Material - Anodized Aluminum
- Gullco Model # GK-200-RHB Kat Track Weld Carriage and Track
- Gullco Electronic Seam Tracker
- Current Type: Constant Current (CC)

Table 5 – Final set of welding conditions chosen for demonstration of the HDGMAW technique with the 3/32” (2.38mm) diameter welding wire, using the welding system and equipment listed in Table 4

- Current Type: Constant Current (CC)
- Current-Polarity: DC-EP
- Average Amperage: 369 Amp
- Average Voltage: 31.0 Volt
- Travel Speed: 22.9 IPM
- Number of Weld Passes: 1
- Weld Position: Flat Down-Hand (1G)
- Electrode / Filler: Alloy – ER5183, Diameter – 0.093 in. (2.4mm)
- Shielding Gas: Argon, Flow Rate: 50 SCFH
- Preheat Temperature: Room Temperature
- Torch Angle: Work Angle: 0.0, Lead Angle: 15 degrees
- Weld Preparation: 90^0 included angle & 0.080” (2mm) deep Vee groove top preparation
- Joint and Root Gap, below the Vee groove top preparation: 0

The Weld Procedure Specification (WPS) and Weld Procedure Qualification Record (WPQR) for flat down hand welding are presented in Appendix 12. In summary, all required non-destructive and destructive tests met their respective requirements except:

- Ultimate Tensile Stress did not meet the 40 ksi (275.8 MPA) limit. Two of the four required specimens were at 39.9 ksi (275.1 MPA) vs. the 40 ksi (275.8 MPA) limit.
- The root reinforcement requires post weld grinding to meet the > 90 degree reentrant angle requirement.
- The Top (Face) Weld Reinforcement meets the 0.090” (2.29mm) limit, but, was border line.

5.6 Weld Seam Tracking Method Assessment

The HDGMAW technique would be implemented in production through the use of a mechanized system, which consists of a track that translates the welding torch along the joints being welded and a mechanical seam tracking device, attached to the welding head (i.e. torch and its brackets) (Figure 3). This tracking system continuously locates the torch so that the tip of the welding wire and the arc at the required lateral position relative to the joint. To accommodate the stylus of this tracking system (Figures 8 & 10), the original Square-Butt joint in this program was modified to include a 0.080” (2mm) deep top Vee groove preparation with a 90° included angle (Appendix 12) in which it “rides” during the welding operation. The other purpose of this top Vee preparation is to help control the height of the top weld reinforcement.

During the initial development of HDGMA welding parameters in Phase I of this program, Alcoa used the Gullco KAT® rigid track and its torch holding & translating carriage system shown in Figure 3 and referenced in Table 4. Carriage motion in the X direction follows the general direction of the weld seam. To keep the proper position of the welding torch relative to the joints during welding, this system arrangement necessitated manual adjustments to the position of the welding torch in the Y and Z directions. Part of Phase 1 of this program was to identify an inexpensive, effective and relatively simple seam tracking system for weld production with the HDGMAW technique, which will continuously and simultaneously maintain the required position of the torch relative to the joints, in the Y (lateral) and Z (Vertical) directions, dispensing with the need for frequent manual adjustments by the welding operator.

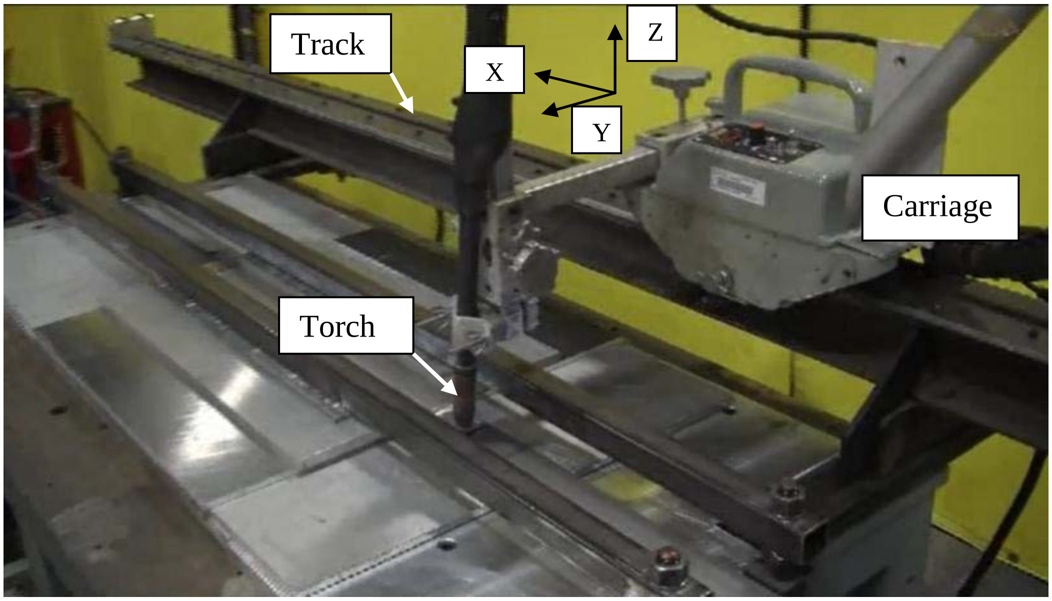

Figure 3 – Mechanized Gullco System Used for HDGMAW Process Development

Commercial seam tracking systems are either laser or tactile probe based. A comparison of the general characteristics of each seam sensing method is made in Table 6.

Table 6 – Seam Tracking Methods Comparison

Feature/Issues	**Laser Vision Seam Tracking**	**Mechanical Probe – Tactile Seam Tracking**
Welding Processes	Applicable to all arc and laser welding processes	Only works with relatively slow (less than 100ipm) fusion based welding processes
Material Type & Condition	Works on any material	Works on any material, although deep gouges, cuts and scratches at the tops of the joints being welded and/or oversized and/or excessively long [e.g. 5" (125mm)] tack welds and/or weld repairs, could compromise tracking effectiveness
Joint Types	Works on any joint type	Only works on tee fillet, lap fillet, groove. Cannot accommodate tight, square butt joints
Installation	Easy to connect and incorporate into the welding head and electrical system	Easy to incorporate into the welding head
Other Equipment Required	None	None

Table 6 – Seam Tracking Methods Comparison (cont'd)

Feature/Issues	Laser Vision Seam Tracking	Mechanical Probe – Tactile Seam Tracking
Search time	Can search for the joint quickly before tracking commences	The stylus must be engaged into the groove by the operator using manual position adjustments prior to initiating the weld process
Repeatability	Laser accurate to microns. Can be programmed to compensate for look-ahead distance	Probe is accurate to millimeters. Cannot compensate for look-ahead distance, i.e. as probe moves so does the welding wire
Material Thickness Limitations	Can go down to 0.020" (0.5mm)	For most joints like butt and lap fillet joints the thickness must be greater than 0.060" (1.5mm)
Flexibility	Can track faster than the welding process and can incorporate weaving if needed	Cannot always track faster than the welding process and cannot handle weaving requirements
Maintainability	Easy to maintain. Its main consumable is the protective lens.	Needs to replace probe as it wears or breaks during collisions
Adaptive Processing	Can measure gap and other joint features which can be used to modify welding parameters in real time. Cannot offset wire precisely.	Cannot measure gap or any joint features
Access	Laser line can be placed at optimum location relative to the torch.	Probe can be placed at optimum location relative to the torch.
Complexity to Learn and Use	A trained engineer or technician is required to select the signal processing filters and parameters and control algorithm parameters. Recommended training is a two day class. Troubleshooting in the field will require a trained engineer and may require technical assistance from the manufacturer.	System is simple to use. Hands on training takes 1-2 hours. The system can be brought on line within 4 hours.
Ability to work when tack welds are used to hold plates	Signal processing and control techniques are available to account for and accommodate tack welds. Control algorithms are very comprehensive for tack weld avoidance.	A simple control algorithm is available to suspend (i.e. skip or fly-blind) tracking when a tack weld is encountered. There are limits to the size of tack welds based on travel speed.
Typical Cost – sensor, servo-motor system, controller, recommended options	$104K	$15K

Even though all seam tracking requirements with the HDGMAW technique could be met with the laser or tactile based systems, the significantly lower cost of the tactile system led to its selection for this phase of the program. Appendices 13 and 14 summarize the capabilities of the Gullco and Servo-Robots' tracking systems.

5.8 Proof of Concept Demonstration of the HDGMA Welding Technique

A major Phase 1 milestone was to weld 5/16" (8mm) thick, 5' (1524mm) long 5083-H116 plates in the flat down hand position, while using the Gullco seam tracking system (Figures 8 and 10) selected in this program. The demonstration took place during a visit by the HPAM program team to the Alcoa Technical Center on February 26, 2013. Figures 4 through 10 present images from a video of the same process.

The first step in the welding process is to prepare the plates. Following the grinding of the top (i.e. side of the top weld reinforcement) edge-bevels (Appendix 12), the edges to be welded and 0.5" (13mm) wide bands on their adjacent parent metals at the top and back surfaces were solvent cleaned, dried, abraded with a rotary hand held stainless steel brush and cleaned (Figure 4).

Figure 4 – Solvent Cleaning and Wire Brush Abrading of Plate Edges

Once the edges of the plates are prepared, they are tack welded together at ~20" (500mm) intervals, starting with tacks at the two ends of the joint, to which removable (or temporary) Run-In and Run-Off tabs are welded. The purpose of these tabs is to help control the quality of the welds at the start and ends of the joints, by starting the welding outside the joint and thus stabilizing the process before welding of the actual joint commences and terminating the weld outside it. To ensure un-interrupted tracking with the tactile sensor, as its probe (or stylus) is "sensing" the location of the joint, ahead of the torch & welding region (i.e. arc and molten pool), the tack welds and Run In and Run Off tabs are grooved in-line with the top Vee preparation of the joint, with the aid of a hand held grinder. Figure 5 illustrates these steps.

 

Figure 5 – Tack Welded Plates and Run In and Run Off tabs, grooved with the aid of a hand held grinder

Once the tack- welded and grooved flat plate assembly is completed, it is placed over the 0.050" (1.27mm) deep recess of the anodized welding backing bar (Appendix 12), which sits on top of the welding table, so the joint to be welded is approximately aligned with the centerline of the backing bar's recess. Aluminum backer plates placed next to the backing bar, support the back sides of the plates to be welded, so the tack welded assembly is nearly parallel to the welding table (Figure 6). The assembly is then secured and held in place with the aid of cambered (i.e. curved) steel clamps (Figures 7B, 8 and 9) and is ready for welding.

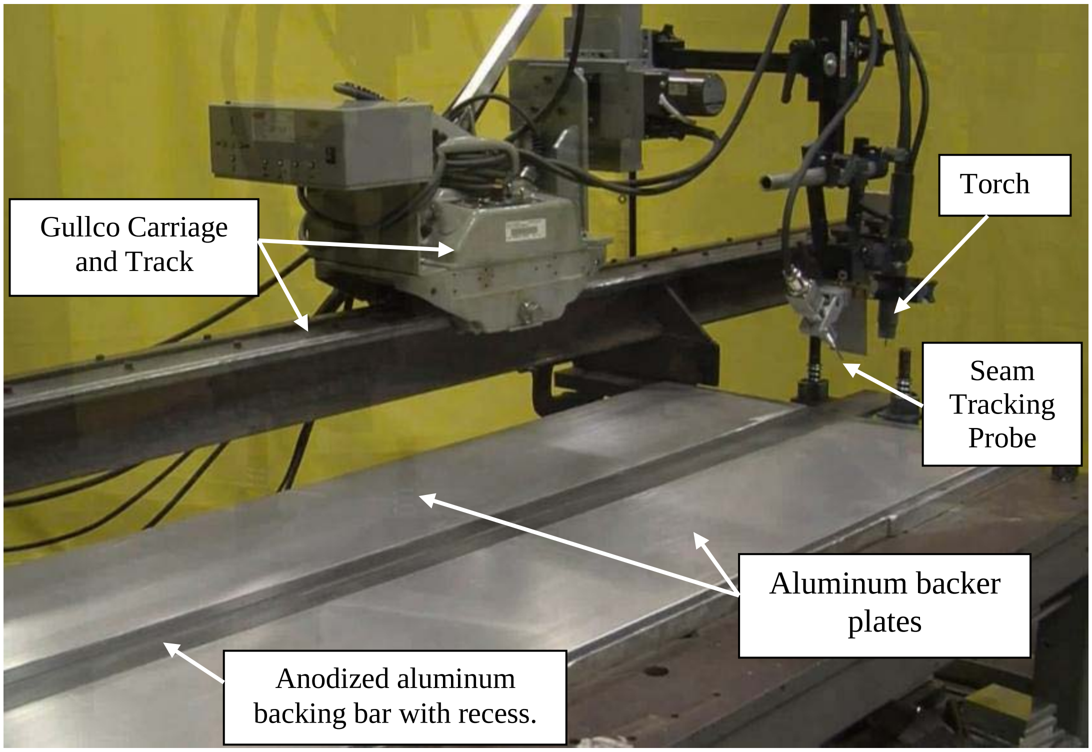

Figure 6 – HDGMA Welding Station at ATC, prior to placement and clamping of the tack welded assembly.

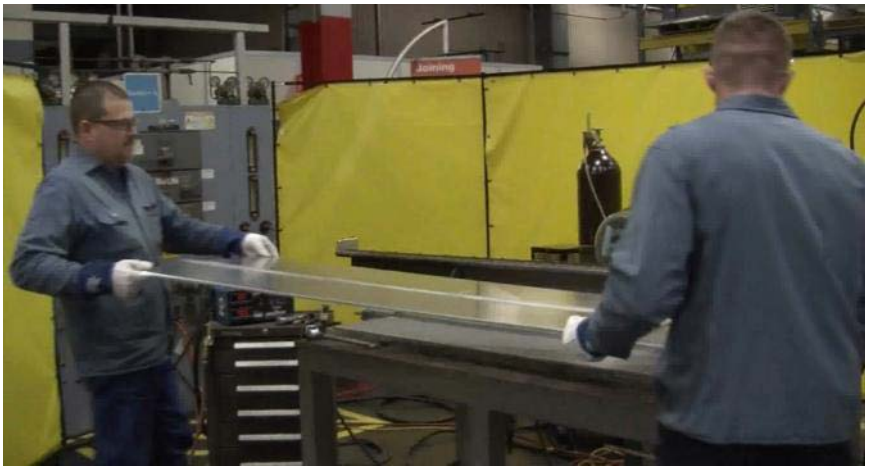

Figure 7A – Plate placement of the tack welded plate assembly onto the welding table over the recessed welding backing bar (not seen) and spacer plates (Figure 8).

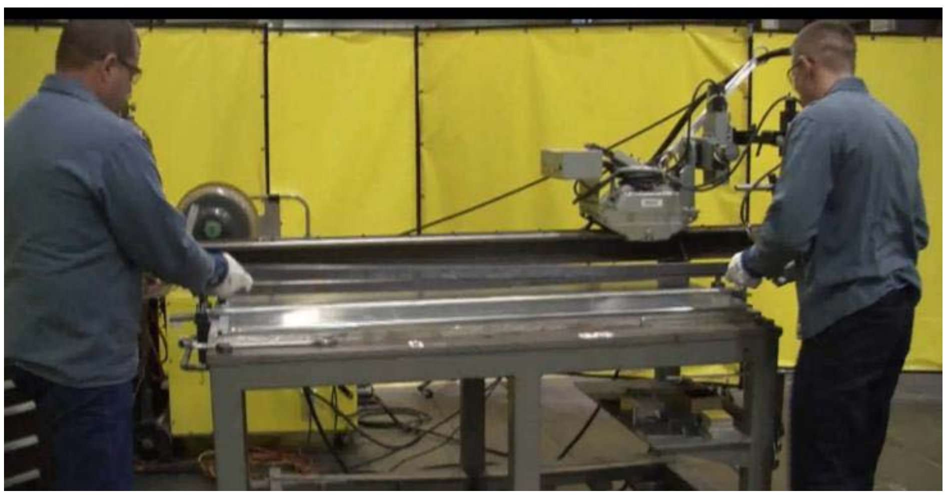

Figure 7B – Placement of the Cambered (Curved) Steel bar over the top of one of the two plates to be welded.

Once the tack welded assembly is placed and clamped in place, the torch and seam tracking system are lowered over and into the top bevel of the joint (Figure 8). To protect the seam tracking system (i.e. top sensor and stylus) from weld spatter and minimize its (i.e. spatter) landing in the joint's top bevel, a spatter/radiation shield is placed between the welding torch and tracker. The torch is positioned over the run-on tab ready for welding to begin.

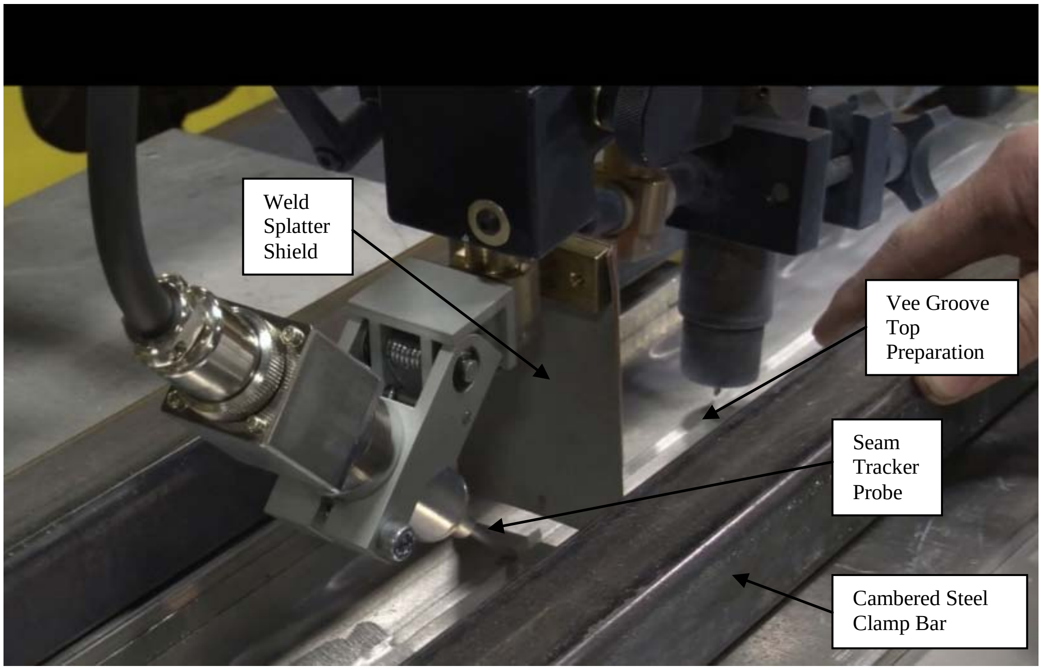

Figure 8 – Torch and Seam Tracking Probe Engaged in Weld Seam

Figure 9 shows the weldment with its top weld in the as-welded condition (i.e. not brushed) and after brushing the smut off it. Tables 4 and 5 respectively present the welding equipment and welding conditions used for producing this demonstration weldment.

Figure 9 – As Welded (left) and Brushed HDGMAW Welded Plates.

Properties of the weld are then evaluated as part of this program. Figure 10 shows the height measurement of the top weld bead.

Figure 10 – Height Measurement of the top weld bead, produced with the HDGMAW technique, with the aid of a dial gauge

5.8 Weld Evaluations and Testing

The conformance of the HDGMA welds in the proof of concept 5' (1524mm) weldments to the requirements specified in Appendix 2, included:

- Visual inspections of the top weld bead and back (root) bead
- Dye penetrant inspections of the top weld bead and back (root) bead
- Radiography
- Measurement of top and back weld bead heights
- Radiography
- Metallographic examination of representative weld cross-sections
- Bend face and bend tests
- Transverse (to the welds) mechanical tests (i.e. UTS, YS and % Elongation).

Refer to Appendix 12 for test results.

5.9 Assessment of feasibility of HDGMA welding in Horizontal Out-of-Position

The feasibility of welding in the Horizontal position with the HDGMAW technique has been successfully demonstrated, with both 3/32" (2.38mm) and 1/16" (1.59mm) diameter welding filler wires. The main thrust of this evaluation revolved around the joint design and welding parameters with each of these two welding filler wires. Starting with the welding parameters developed for welding in the flat down hand position (Table 5) and progressing to trying different welding parameters/joint design combinations, the most promising joint design turned out to be a half bevel, with the bevel machined onto the weld edge of the lower plate. This joint preparation is presented in Appendices 15-2 and 15-3. The primary challenge with welding in the Horizontal position was to achieve the delicate balance between the surface tension of the molten pool and the constant gravitational pull on it from the instance of its deposition followed by its solidification. When these two variables are not balanced, the Horizontal welds tend to develop a pronounced undercut at the upper (i.e. away from the ground) toe (or edge) of the outer (versus top in the flat down hand welding position) and larger weld bead. As a result, the efforts to weld in this position concentrated on simultaneously maintaining a stable arc and controllable flow & solidification of the molten pool, while trying to consistently achieve the weld attributes (i.e. geometry and sound weld quality) that meet the specified requirements in Appendix 2. Appendix 15-1 shows the weld fixture set-up used for Horizontal Out of Position (OOP) welding and a representative cross-section. Appendix 15-2 and Appendix 15-3 present the conditions that yielded the "most promising" results with the with the 3/32" (2.38mm) diameter welding filler wire and the 1/16" (1.59mm) diameter welding filler wire, respectively.

Representative welds produced in the Horizontal position with both diameter welding wires, were tested with non-destructive and destructive tests. However, some of the tests were not completed prior to the termination of the program. The tests showed that:

1. The welds, whose representative cross-sections were checked by metallographic examination, contained a moderate amount of porosity at its upper portion (Appendix 15-1). To better quantify the level of weld porosity in this weld and check whether it meets its allowed level (Appendix 2), will require its radiographic inspection. The planned radiography was not carried out, due to the termination of the program.
2. The height of the top weld reinforcement was typically between 0.090" (2.29mm) and 0.105" (2.67mm), which is similar to the results obtained with HDGMA welds produced in the Flat Down Hand position.
3. Dye Penetrant tests on the representative weld had no indication of surface breaking discontinuities (e.g. cracks, pores, etc.).
4. Face and Root Bend tests passed without cracking in the weld and/or the parent metals. The bend tests were of the Wrap-Around type using a 6.66T anvil diameter, where T is the thickness of the parent metal.

Preliminary evaluations of the HDGMAW technique's tolerance to concurrent variations in joint gap and vertical mismatch between the parts, while welding in the Horizontal position, show that the technique can tolerate a maximum 0.060" (1.5mm) joint gap & 0.040" (1.0mm) vertical mismatch between the parts being welded. This is comparable to the tolerance to parts fit up achieved when welding in the Flat Down Position (Appendix 11 – Figure A11-11).

The remaining Destructive Tests were discontinued when the program was terminated.

5.10 Testing of HDGMAW for Acceptance as a New Weld Process

Because the HDGMAW technique is considered as a new process by some members of the NAVSEA team, they requested additional tests of weldments produced with this method, as part of its qualification. Appendix 4 presents NAVSEA's e mail of July, 2, 2012 in which they specify the type of additional tests. Of the specified tests in this email, Porosity, Corrosion and Weld Distortion evaluations were completed prior to the-termination of the program.
To carry out the additional tests requested by NAVSEA, the member shipyards were provided with six 5083-H116 plates each being 2' (610mm) long x 1' (305mm) wide and 5/16" (8mm)

thick. These plates were to be welded by the member shipyards with the Gas Metal Arc Welding (GMAW) process, using their welders and qualified procedures. Two of these plates were used for weld procedure verification and the remaining four plates were welded into two separate test weldments, to be used as the baseline against which to compare the two HDGMA test weldments produced at the Alcoa Technical Center. The Baseline and HDGMAW weldments were tested in the exact same manner. The tests and comparisons of results between the Baseline GMA and HDGMA weldments, are presented below:

5.10.1 Porosity

Porosity was assessed by metallographic examination of representative cross-sections and radiography of the welds. The radiography of the welds was done both in the as welded condition, where the top and back (root-side) weld beads were left intact and post-machined condition where both of these beads were removed flush with the top and back side surfaces of the weldments. Both the single pass HDGMA and multi-pass Baseline GMA welds contained acceptable levels of porosity. The single pass HDGMA Welds had 90% less porosity than the multi-pass Baseline GMA welds. Representative cross-sections of HDGMA and Baseline GMA welds are shown in Appendix 16-1.

5.10.2 Corrosion

Corrosion Comparison on HDGMAW to Baseline GMAW was done using the XM-308 24hr ASSET (ASTM G66) test. The tests were performed on the top and root sides of the weld in the as welded condition and following a seven day exposure to 100^0 C. The corrosion resistance of the Baseline GMA and HDGMA welds were comparable. There was no evidence of Exfoliation Type Corrosion in any of the weldments produced with either of the processes. Some pitting corrosion was seen, which is expected with this type of test. All specimens produced with the two welding techniques in the as welded condition passed with a rating of PA. All specimens produced with both processes passed with a PB rating following a seven day exposure at 100^0C. There was no evidence of preferential corrosion in the HAZ. There was some enhanced pitting corrosion in Baseline GMAW in the Parent Material. At this point, neither the significance of this enhanced pitting in the Baseline GMA weldments nor its cause, are known. Detailed ratings and pictures of the test specimens are shown in Appendix 16-2.

5.10.3 Weld Induced Distortion

The plates were measured with a Coordinate Measurement Machine (CMM) prior to welding. The plates were marked so that measurement reference points were re-used for the post weld measurement, thus implementing a coordinated measurement. This enabled the post weld CMM measurements for out of plane distortion and lateral shrinkage to be made at the same locations as the pre-weld measurements. Also, this allowed any deviation in the component parts to be subtracted from post weld measurements so that the distortion calculation did not include any contribution from the component part tolerances.

The plates used for the GMAW to HDGMAW comparison test weldments had very low levels of deviation from flat. Also, the width of plates [1’ (305mm) dimension] was closely controlled because the edges of the plate were machined. This provided for a very good gap and vertical mismatch at fit-up and it minimized any impact of the components on the weld distortion measurement.

The weld distortion measurements for the HDGMAW and the Baseline GMAW processes are shown in Appendix 16-3. The plots are a top view of the weldment with the weld face labeled. The location of the Z (up/down) reference points are shown. The datums for the Y direction were on the bottom edge, so, lateral shrinkage across the weld will be evident on the edge measurements shown at the top of the page. Each measurement point is shown with a deviation box. The sign convention is such that measurements with a positive deviation are proud of the pre-weld measurement and those with a negative deviation are shy or the pre-weld measurement. The deviation boxes are also color coded. Positive deviations have warm colors (yellow, orange, red) and negative have cool colors (green, cyan, blue). Any deviations outside ±0.080” (±2mm) are red (positive) or blue (negative). The Baseline GMAW had higher out of plane distortion than HDGMAW by a factor of 4.5X. Also, the Baseline GMAW has higher lateral shrinkage by a factor of 2.4X. These are significantly higher levels of distortion and shrinkage. This significant improvement with the HDGMAW technique stems from the combination of lower total welding heat input per linear length, achieved with deposition of a single weld pass, and the complete penetrating of the weld through the joint, resulting in a more balanced weld induced distortion about the joint’s neutral axis.

5.11 Cost Modeling of the HDGMAW and Manual GMAW Processes

A detailed cost model was completed as part of Phase I. This is based on the material thicknesses, weld lengths in the design and the weld positions in the assembly sequence. The complete report for this cost model is presented in Appendix 17.

The cost model was created using the SEER-MFG commercial cost estimation software system. This system is employed by several major Defense Original Equipment Manufacturers. Labor, material, and tooling estimates for major steps are developed based upon industry standards. These include plasma cutting, routing, material transfer, part fit-up, multi-pass GMAW welding, inspection and rework operations. Labor costs are based upon time standards (calculated by SEER-MFG) and labor rates that are assigned by user. The user has the ability to add multiplication factors to adjust the standard rates form the SEER-MFG database.

The cost assumptions including labor rates and consumable costs are given in Appendix 17 Figure A17-2. Non-recurring costs are not included in the cost model. Non-recurring costs were considered by the limits on the cost of the HDGMAW systems for Flat Down Hand and Out of Position welding that were part of the Go-No Go Criteria for the project.

The primary inputs to the cost model were the flow paths for the Baseline GMAW and HDGAMW processes. Flow paths were developed for two cases for each process: Panel Line welding of panels or plates in the Flat Down Hand Position and welding in Module Erection or Final Erection in either the Flat Down Hand, Horizontal or Vertical Positions. The flow paths are presented in the following figures.

- Appendix 17, Figure A17-3 – Panel in Module Build – Baseline GMAW – FDH Position
- Appendix 17, Figure A17-4 – Panel in Module Build – HDGMAW – FDH Position
- Appendix 17, Figure A17-6 – Module to Module Erection – Baseline GMAW
- Appendix 17, Figure A17-7 – Module to Module Erection – HDGMAW

The detailed breakdown of the cost comparison for a Panel Line Flat Down Hand Position weld with both process is presented in Appendix 17, Figure A17-5. This figure presents the cost of each flow path step for both processes including the labor hours per unit and the labor cost per unit. For the HDGMAW process, there is an additional comment on the relative cost of each flow path step relative to Baseline GMAW. There are some steps that the cost is estimated to be exactly the same for both processes. Others are a similar step, but, are estimated to involve more labor for HDGMAW than what is required for the Baseline GMAW. This is noted with the assumed labor multiplier. The cost of the actual welding with HDGMAW is based on the welding speed demonstrated during Phase I welding. Finally, the total estimated cost savings for this particular weld joint is summarized. Appendix 17, Figure A17-8 presents a similar comparison for a module to module weld.

Appendix 17, Figure A17-9 shows the cost comparison for all applicable welds in the complete structure. This includes both panel to panel and module to module welds. These welds are in multiple positions: Flat Down Hand, Horizontal Out of Position and Vertical Out of Position. The average estimated cost savings of all these welds was 22%. Appendix 17, Figure A17-10 shows only welds in the Flat Down Position. The average estimated cost savings of all these welds was 21%.

One element of the flow path that is difficult to estimate in a cost analysis is the labor time for part fit-up. This is highly dependent upon the geometry of the parts, the assembly sequence and the effect of component tolerances and weld distortion from previous welds. The HDGMAW process will require tighter control of joint gap and vertical mismatch to achieve consistent weld quality. So, there will be higher labor cost to achieve the required joint gap and vertical mismatch. It was estimated that this would be 1.5X the labor of the Baseline HDGMAW. Feedback from the shipyards is that this factor should be higher and, in fact, it may not be feasible at all to meet these limits in some conditions. So, a sensitivity analysis was done to find the breakeven point for the HDGMAW process as a function of the multiplier used for the fit-up cost component. Appendix 17 Figure A17-11 presents the cost savings as a function of this multiplier. The savings for the HDGMAW process is reduced to zero if the labor required for fit-up for the HDGMAW process is ~2.6X of the Baseline GMAW process fit-up labor component. Note that all welds in the cost model are for 5/32” (4mm) thick material. There would further savings available for thicker materials which would require additional weld passes with the Baseline GMAW process. This would increase the factor for the breakeven point.

5.11.1 System Integrator Survey

This survey was not completed prior to the termination of the program. However, discussions were held with six system integrators during Phase 1 activities. At the beginning of Phase 1, five of the system integrators were invited to give presentations on their capabilities. The general requirements of the planned system were reviewed with the system integrators during these meetings. A detailed system specification was not given, however. The system integrators were asked for a rough order of magnitude (ROM) quote for a system to be used in Phase 2 using their best judgment of meeting requirements that were reviewed during their visits. They were also asked to express any concerns they had with the technology or the project. The sixth system integrator provided a preliminary quote for the project proposal. All six system integrators were technically capable of providing the system for Phase 2 of the project. Two of the six system integrators declined to provide a quote and were omitted from further consideration. The quotes and interactions with the System Integrators indicated to the Alcoa team that there were viable candidates for Phase 2. The final down selection was not completed and the request for quote for the Phase 2 System was not pursued because of the decision to terminate the project.

5.11.2 Specification for Phase 2 HDGMAW System

The specification for the Phase 2 HDGMAW System was not initiated prior to termination of the program. It will not be included in this report.

6.0 Welding Performance Versus Targets Checklist

Acceptance criteria for high deposition GMA welds were developed to guide a recommendation concerning the continuation of this program into Phase 2. These criteria are listed in the "Go / No Go" checklist in Appendix 18. This checklist consists of a listing of a Parameter or Performance Requirement, Target Metric, the Demonstrated Performance, Pass/Fail Indicator and a field for Comments.

Physical properties measured were from welded plates produced on the prototype High Deposition Gas Metal Arc Welding (HDGMAW) system configured at the Alcoa Technical Center. Welds up to 5' (1524mm) long were produced on this equipment from 5083-H116 plate using 5183 filler wire.

Where ever possible, the metrics were determined from the Targeted Weld Attributes (Appendix 4) and applicable Military & NAVSEA standards. Some criteria on the "Go / No Go" checklist use a comparison with standard GMA welded plate to provide directional information for the Phase 2 recommendation because standards do not include criteria for these parameters. The standard GMA data were obtained from welds produced on the same lot of 5/16" (8mm) thick 5083-H116 plate welded at a shipyard.

There are forty Parameter or Performance Requirements in the Go/No Go Checklist. Five of these failed to meet the Target Metric. Evaluations for seven were not completed prior to the termination of the program.

7.0 Project Risk Assessment

The Office of Naval Research maintains a continuous understanding of a program's ability to be implemented through a periodic Project Risk Assessment (PRA). This standard document is completed for all ManTech Programs. The HPAM program's PRA as reported at the LCS IPT April 25, 2013, meeting is contained in Appendix 19.

8.0 Phase 1 Conclusion

Technical characteristics of the HDGMAW technique were reviewed by CNST and the shipyards toward the end of Phase 1, to determine the likelihood that this welding technique will be adopted and implemented by the shipyards at the conclusion Phase 2 of this program. They have concluded to terminate the program, because they rendered this technique unlikely to be used in current production at the Austal and Marinette shipyards. The three main factors that led to this decision were:

1. The capability of the HDGMAW technique to weld joint gaps and part vertical mismatches only up to a maximum of 0.080" (2mm).
2. The need to use temporary backing bars as this is an additional step in joint fit-up.
3. The need to grind-blend the toes (or edges) of the back side (or root) of the welds produced with this welding technique, in order to guarantee the required >90° reentry angle as specified in Appendix 4.

It was felt these factors would reduce the economical benefit of HDGMAW sufficiently to preclude its use. CNST recommended, and ONR agreed, that the HPAM program would end after the Phase 1 cost modeling and summary reporting tasks were completed.

Also, there were two elements of the Weld Procedure Qualification that were not met. The Ultimate Tensile Stress requirement was not met and the Top (Face) Weld Reinforcement Height was on the borderline of its requirement. These requirements would require further development to resolve if they could not be accepted as exceptions to the applicable NAVSEA standards.

Given all results from Phase I and the recognized need for further development to meet all Go/No Go criteria, the most likely future application of the HDGMAW in the shipyard industry would be a traditional panel line with thicknesses at the upper end of the 5/32"-5/16" (4mm-8mm) thickness range. This type of application would reduce the cost impact of placing the temporary backing bar and would increase the benefit from the reduced number of welding passes.

9.0 Acronyms

ATC – Alcoa Technical Center, located 20 miles east of Pittsburgh, PA

CMM – Coordinate Measurement Machine

CNST – Center for Naval Shipbuilding Technology

FDH – Flat Down-Hand

GMAW – Gas Metal Arc Welding

HAZ – Heat Affected Zone

HPAM – High Productivity Aluminum Manufacturing

HDGMAW – High Deposition Gas Metal Arc Welding

IPM – Inches per minute

LoF – Lack of Fusion

ONR – Office of Naval Research

OOP – Out of Position

PRA – Project Risk Assessment

SSSP – Single Side, Single Pass

TBB – Temporary Backing Bar

TYE – Material mechanical properties: Tensile Stress, Yield (Ultimate) Stress, Elongation

WPQR – Weld Procedure Qualification Record

WPS – Weld Procedure Specification